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(54) **SENSOR INTERFACE WITH VARIABLE CONTROL COEFFICIENTS**

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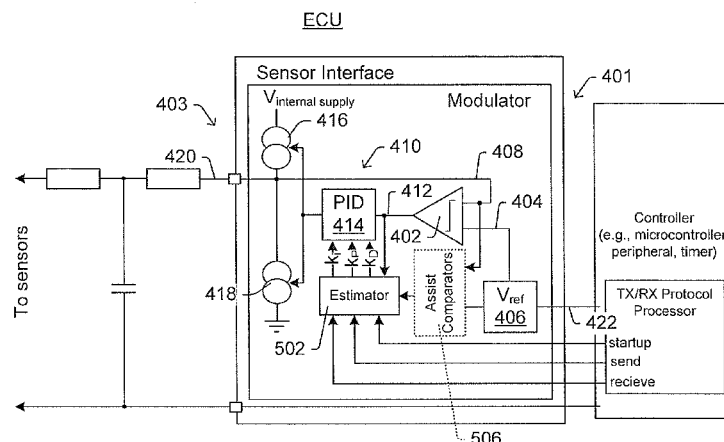
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(57) **ABSTRACT**

The present disclosure is directed towards a sensor interface module that delivers a supply voltage to a plurality of sensors, and which exchanges data signals between the plurality of sensors and a control unit (e.g., an ECU). The sensor interface often employs a single-bit comparator (or a coarse analog to digital converter (ADC), e.g., a 2-bit or 3-bit ADC) to track signals to be exchanged between the sensors and controller over the sensor interface. Compared to power hungry ADC with more bits (e.g., 32 bit ADC), the single-bit comparator/coarse ADC limits hardware complexity and power consumption. In addition, in some embodiments the sensor interface module can include an estimator and assist comparators to speed up the tracking ability of the sensor interface module. In this way, techniques provided herein facilitate reliable, low-power communication between a control unit (e.g., an ECU) and its corresponding sensors.

8 Claims, 6 Drawing Sheets



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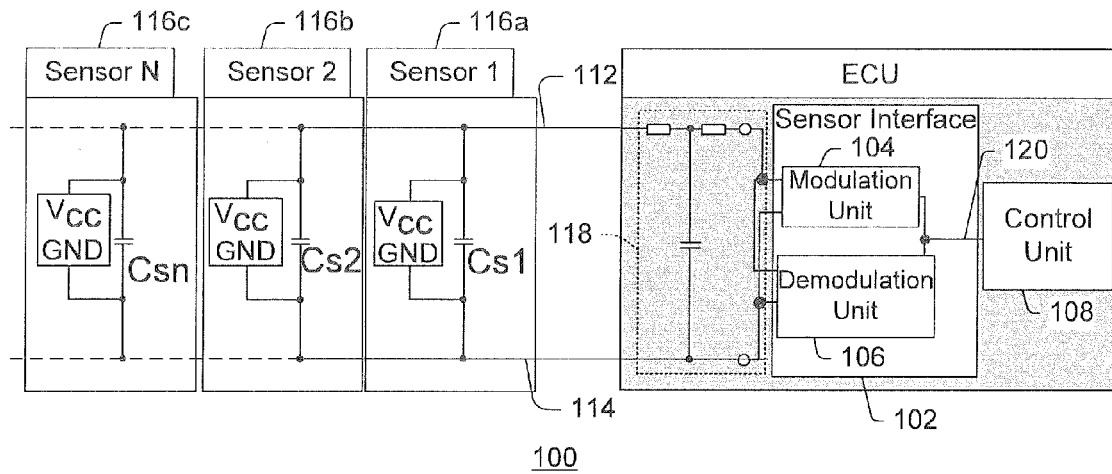


FIG. 1

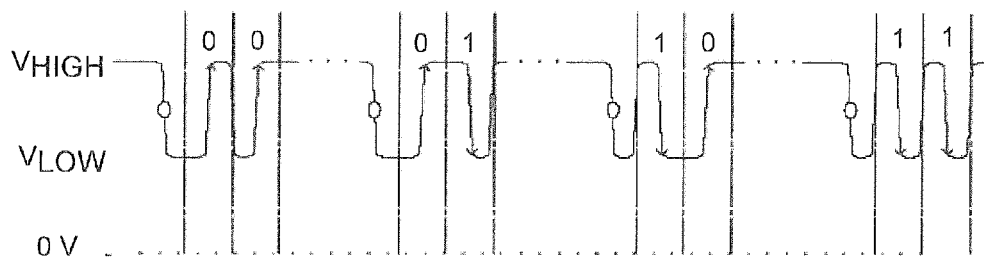


FIG. 2

Response data bit encoding

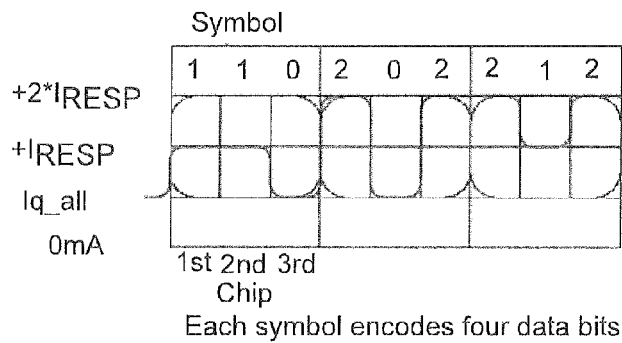


FIG. 3

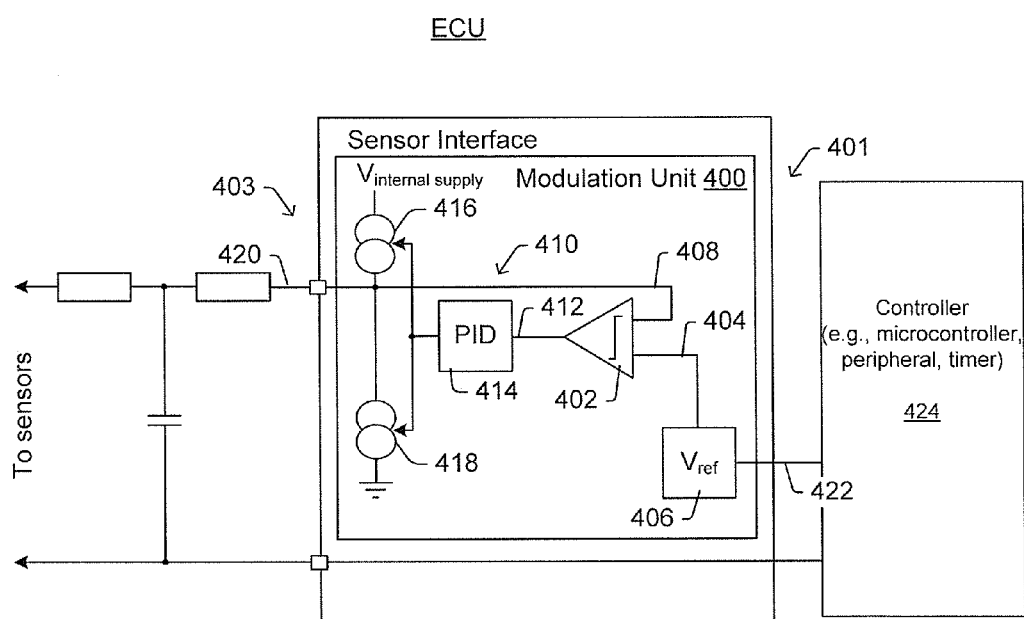
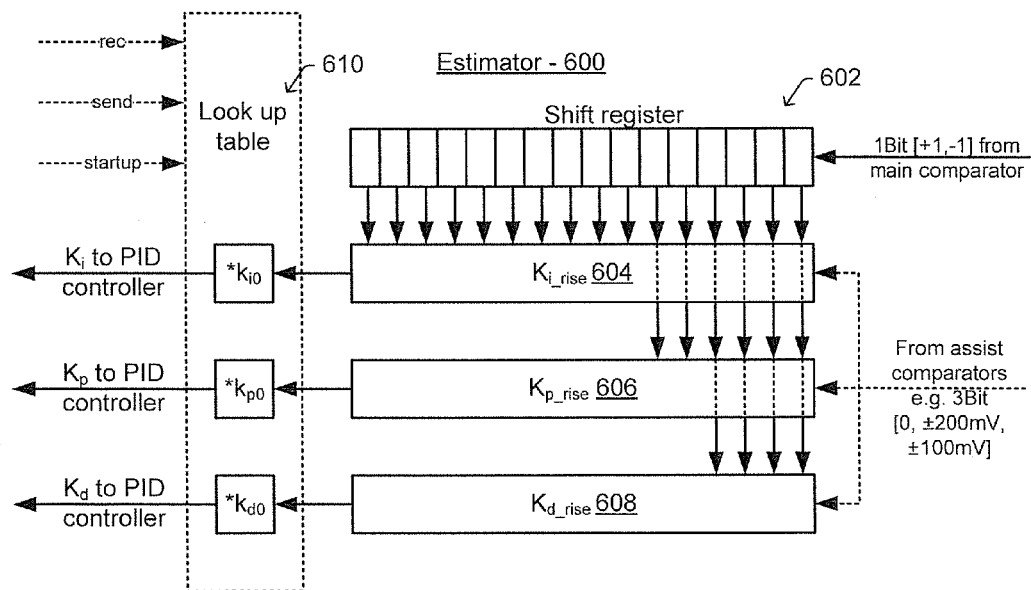
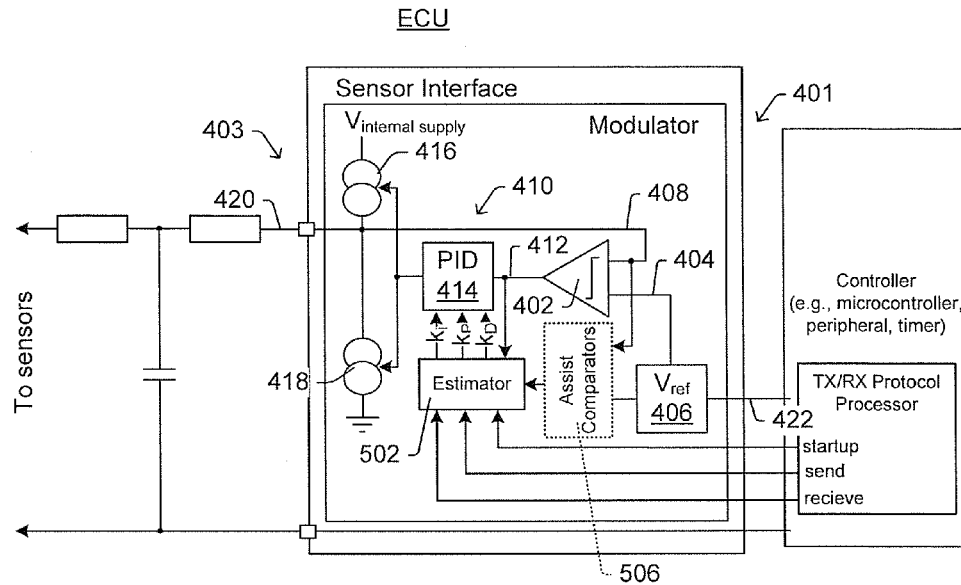


FIG. 4



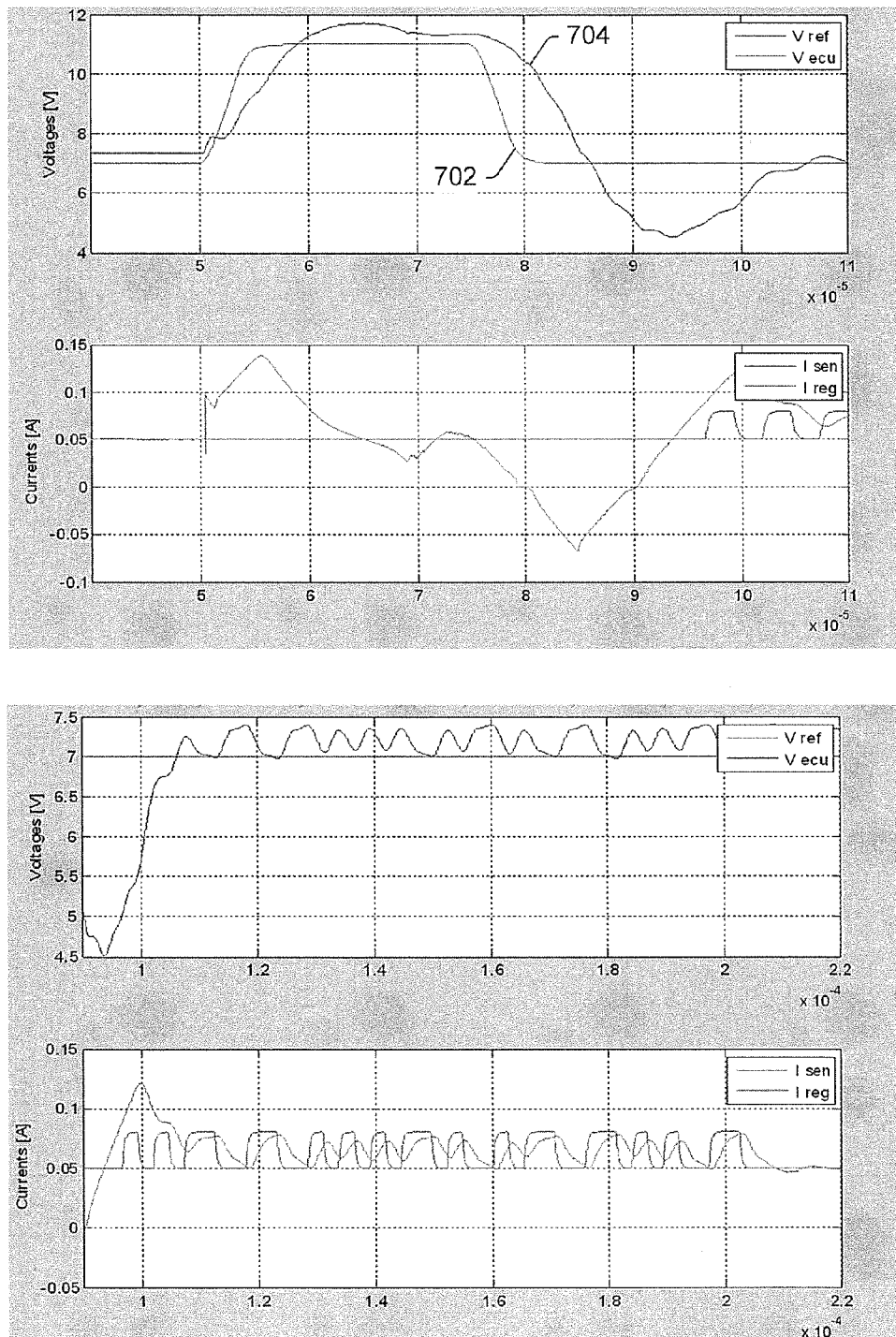


FIG. 7A

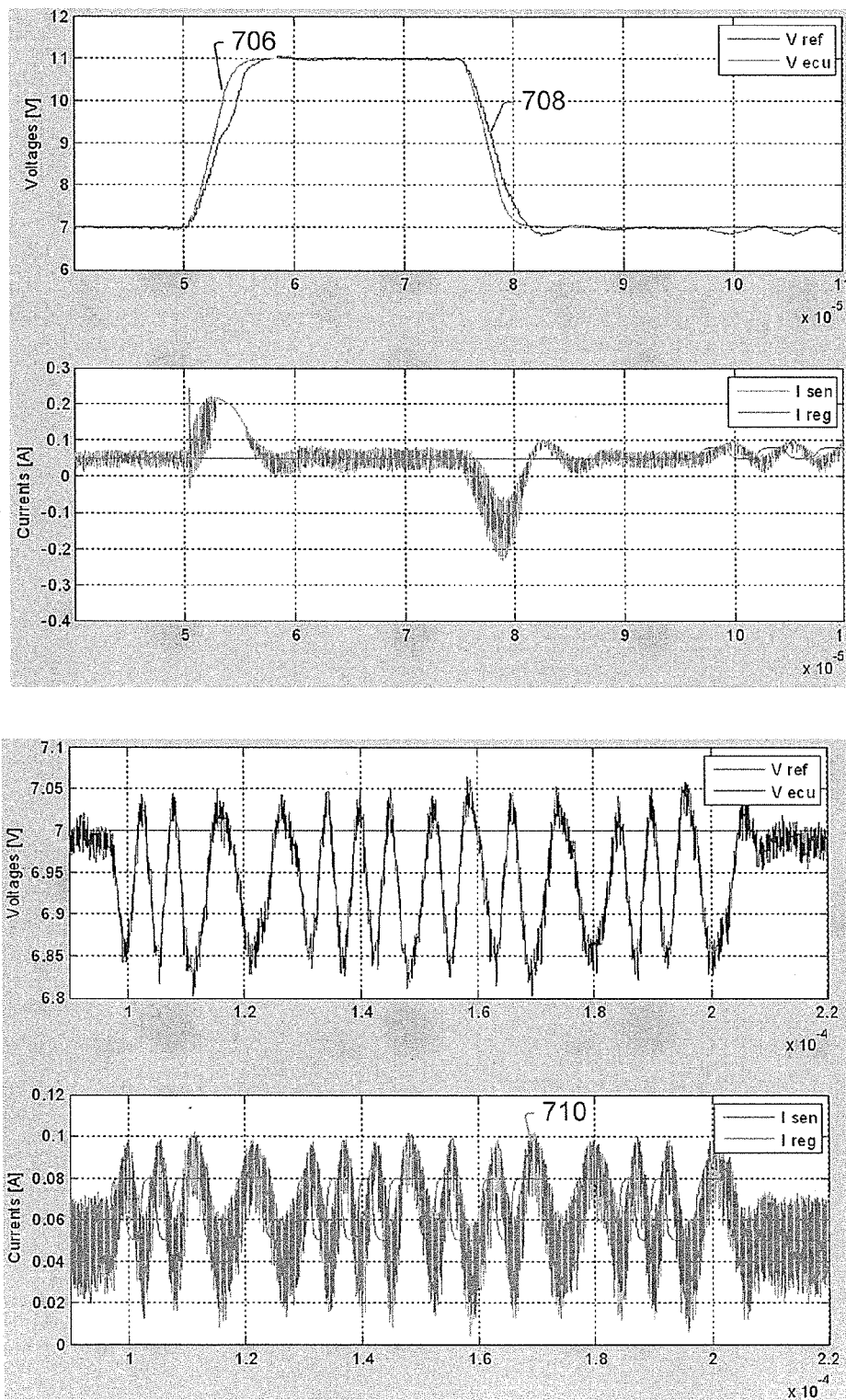


FIG. 7B

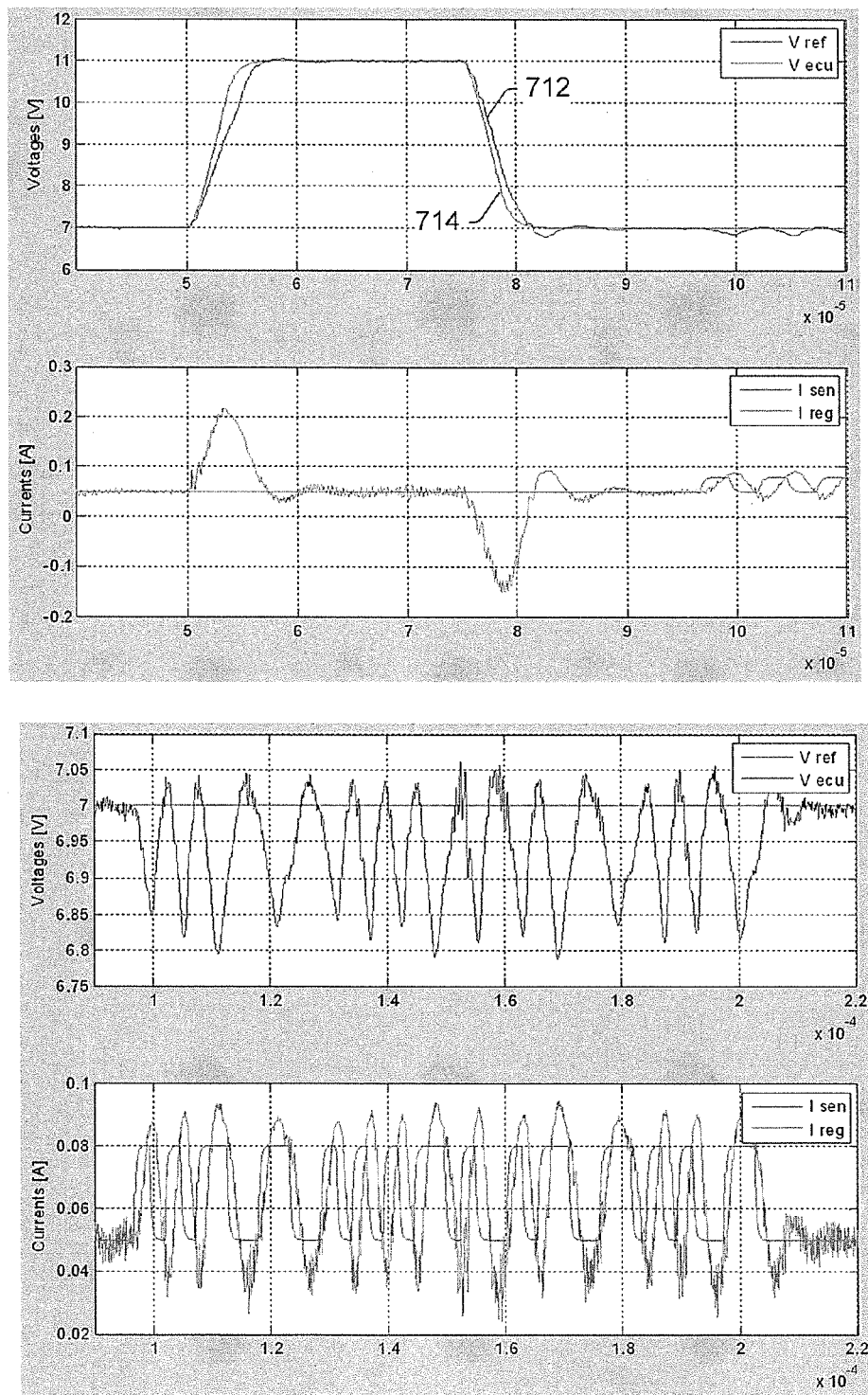


FIG. 7C

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SENSOR INTERFACE WITH VARIABLE CONTROL COEFFICIENTS

BACKGROUND

Modern vehicles include a vast array of sensors, such as air bag sensors, tire pressure sensors, engine sensors, seat belt sensors, and many others. The engine sensors, for example, can provide data about the vehicle's engine cycle to an engine control unit (ECU). Based on the data from the engine sensors, the ECU can then make changes to the engine cycle (e.g., spark plug timing and/or fuel injection parameters) to optimize engine performance.

As the number of vehicular sensors increases, integration is becoming a serious challenge for automakers. For example, wires connecting an ECU to its corresponding engine sensors can be several meters long. These wires are a significant cost factor in automotive systems and contribute to the overall weight of the vehicle. Because of this, some conventional wiring interfaces, such as PSI5 and DSI for example, limit the number of wires to two lines. These interfaces can be used in automotive airbag sensors, power train systems, and non-standardized pulse width modulated (PWM) protocols of ABS wheel speed sensors, among others. Unfortunately, absent countermeasures, the inductances and capacitances of these wires can give rise to noise at a resonant frequency set by the inductances and capacitances of the wires.

In some conventional implementations, an RLC filter (which includes a resistor and an optional by-pass inductor in parallel with the resistor) may be arranged between an ECU and its corresponding sensors. This RLC filter can be designed to attenuate noise at the resonant frequency, thereby helping to improve the performance of the vehicular sensing system. Unfortunately, however, the resistor and inductor included in such an RLC filter consume power, add to the cost of the sensor system, and may cause a voltage drop thereover. In addition, because different vehicles may include different sensors and different lengths of wires (i.e., different inductances and capacitances), it is difficult to set a single RLC filter to adequately attenuate the different resonant frequencies corresponding to the different vehicles in conventional sensing systems.

Therefore, conventional approaches are less than ideal for several reasons, and the inventors have devised improved sensor interfaces as described further herein.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a vehicular sensing system in accordance with some embodiments.

FIG. 2 is a waveform diagram of a modulated voltage signal that can be transmitted to sensors of a vehicular sensing system.

FIG. 3 is a waveform diagram of a modulated current signal that can be transmitted from a sensor of a vehicular sensing system.

FIG. 4 is a block diagram of a sensor interface module in accordance with some embodiments.

FIG. 5 is a block diagram of another sensor interface module in accordance with some embodiments.

FIG. 6 is a block diagram of an estimator block in accordance with some embodiments.

FIGS. 7A-7C are waveform diagrams of a modulated voltage signal and corresponding currents for various sensor interface modules.

DETAILED DESCRIPTION

The claimed subject matter is now described with reference to the drawings, wherein like reference numerals are used to

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refer to like elements throughout. In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the claimed subject matter. It may be evident, however, that the claimed subject matter may be practiced without these specific details.

The present disclosure is directed towards a sensor interface module that delivers a supply voltage to a plurality of sensors, and which exchanges data signals between the plurality of sensors and a controller (e.g., an ECU). The sensor interface often employs a single-bit comparator (or a coarse analog to digital converter (ADC), e.g., a 2-bit or 3-bit ADC) to track signals to be exchanged between the sensors and controller over the sensor interface. Compared to power hungry ADC with more bits (e.g., 32 bit ADC), the single-bit comparator/coarse ADC limits hardware complexity and power consumption. In addition, in some embodiments the sensor interface module can include an estimator and/or assist comparators to speed up the tracking ability of the sensor interface module. In this way, techniques provided herein facilitate reliable, low-power communication between a controller (e.g., an ECU) and its corresponding sensors.

Turning now to FIG. 1, one can see a vehicular sensing system **100** that includes a sensor interface module **102** in accordance with some embodiments. The sensor interface module **102** includes modulation unit **104** and demodulation unit **106**. On one side, the sensor interface module **102** has a control unit interface coupled to a control unit **108** (e.g., ECU); and on the other side, the sensor interface module **102** has a sensor interface coupled to a pair of wires **112, 114**. The pair of wires are coupled to a number of sensors **116** (e.g., **116a, 116b, . . . 116c**). To limit noise, an RC filter **118** is coupled to the sensor interface. In many embodiments, the RC filter **118** is devoid of discrete inductors and integrated inductors to reduce costs.

During operation, and when no data is to be exchanged, modulation unit **104** provides a supply voltage to the sensors **116** via the pair of wires **112, 114**. This supply voltage is often a DC voltage used to power the sensors **116**.

When information is to be transmitted to the sensors **116**, the control unit **108** provides a first control signal on **120**. Based on the first control signal, the modulation unit **104** modulates the supply voltage to deliver a modulated voltage signal to at least one of the sensors **116** via the pair of wires **112, 114**. FIG. 2 shows one example of how this modulated voltage signal **200** can vary the supply voltage between a high supply voltage (V_{HIGH}) and a low supply voltage (V_{LOW}) to transmit information to the sensors **116**. In FIG. 2's example, a rising edge voltage transition corresponds to a logical "0" and a falling edge voltage transition corresponds to a logical "1", but other encoding schemes could also be used.

To receive information from the sensors **116**, the demodulation unit **106** decodes a modulated current signal received on the wires **112, 114**, wherein the modulated current signal includes information from a transmitting sensor (e.g., **116a**) contained therein. FIG. 3 shows one example of a modulated current signal **300** that contains encoded data thereon as transmitted by a sensor. In FIG. 3's example, data bits can be encoded as symbols on the wires **112, 114**, wherein each symbol is made up of three chips and encodes four data bits.

FIG. 4 shows a more detailed view of a modulation unit **400** (e.g., modulation unit **104** of FIG. 1). On one side, the modulation unit **400** includes a control unit interface **401**, which interfaces to a control unit **424**. On the other side, the modulation unit **400** includes a sensor interface **403**, which interfaces to the pair of wires coupled to the sensors. In short, the modulation unit **400** receives a first control signal on **422**, and

regulates its output voltage on output node **420** such that the output voltage tracks the first control signal **422**, thereby transmitting the desired information to the sensors.

To limit power consumption, rather than using a power-hungry ADC with a large number of bits (e.g., 32 bit ADC), the modulation unit **400** includes a single-bit comparator **402** to output a single-bit error signal on **412**, or which uses a coarse ADC to output an error signal having only a few bits (e.g., 2 or 3 bits) on **412**. For the single-bit comparator **402**, a first comparator input **404** is coupled to a supply voltage **406**, and a second comparator input **408** is coupled to the output node **420** via a feedback path **410**. The comparator output **412** is coupled to a PID controller **414**, which is in turn coupled to first and second current sources **416**, **418**.

During operation, FIG. **4**'s modulation unit **400** can change its output voltage on output node **420** based on a first control signal **422** from controller **424**. This first control signal on **422** sets a target voltage on the first comparator input **404**. The comparator **402** then adjusts its error signal voltage level on **412** (which sets a second control signal output by the PID controller) until the modulation unit's output voltage on output node **420** matches the target voltage on **404**. Even though the single bit comparator **402** potentially provides low-power performance and minimum chip area, however, the inventors have appreciated that unfortunately the single-bit comparator architecture is fraught with challenges. The sampling rate of the comparator **402** is typically high compared to the bandwidth of the PID controller **414**. Thus, large difference between the output voltage and the target voltage cannot be compensated during a single clock cycle. Absent countermeasures, the limited bandwidth of the controller emphasizes the nonlinearities of the coarse quantized feedback path and lets the loop go into a slewing state. If this slewing is not finished fast enough it can prevent the sensor interface from tracking currents or voltages fast enough to accurately exchange data between controller **424** and its corresponding sensors.

To help facilitate use of a single-bit comparator (or coarse-bit ADC), some modulation units disclosed herein make use of an estimator block. For example, in FIG. **5**, an estimator block **502** updates coefficients for the PID controller **414** based on a history of feedback on the feedback path **410**. For example, when the comparator **402** is a single-bit comparator and the feedback path **410** is a single-bit feedback path, the estimator block **502** can receive a series of single bits from the feedback path **410** at different times, and then analyze the collective single bits to set the PID coefficients (e.g., k_i , k_p , k_d). The estimator block **502** is also coupled to a protocol processor **504** to take into account whether information is to be transmitted to the sensors, received from the sensors, and whether the estimator **502** is in a startup mode.

Because large differences between the output voltage on **420** and the target voltage on **404** cannot be compensated during a single clock cycle, several consecutive feedback bits will have the same value for large differences. Consequently, the number of consecutive samples having the same sign gives a measure that is reciprocally related to the gain of the single bit comparator **402**. This gain estimation principle allows the continuous increase of the PID coefficients unless the sign of the error signal on **412** switches.

FIG. **5** also shows how one or more optional, assist comparators **506** can be included in some modulation units. If present, these assist comparators **506** have respective reference voltages set at different trigger points. For example, if there are three assist comparators, they can have respective reference voltages at 50 mV (e.g., "large" deviation between target signal and output signal), 100 mV (e.g., "very large" deviation between target signal and output signal), and 200

mV (e.g., "excessive" deviation between target signal and output signal). These assist comparators **506** allow the sensor interface module to change control characteristics more rapidly than with a single bit comparator alone (e.g., for gain estimation based on an N-bit FIR filter, since it needs N steps to teach its maximum output value). In essence, the assist comparators **506** can each provide additional gain to help assist the single-bit comparator **402** when large changes in the output voltage are needed. Furthermore the assist comparators **506** can switch their outputs to deactivate the additional gain when the output approaches the target value again, which improves the ability to avoid overshoot or oscillation after slew transitions. These assist comparators **506** can be realized in extremely simple, chip-area saving and power saving manner, and are especially useful to react to electromagnetic injection. But for the assist comparators **506**, electromagnetic injection can exceed the assist comparator threshold within very few clock cycles and requires a very fast proportional and differential response.

In considering how to set the PID coefficients, the estimator block **502** can account for the frequency of the error signal, as follows:

K_i coefficient—the integral coefficient (K_i) is dominant at low frequencies (e.g., where the frequency of the error signal is less than a factor between 100 and 10,000 of the sample frequency (f_s)). Thus, k_i is dominant for error signal frequencies of between below $f_s/10,000$ and $f_s/100$. Adaptation can be fast enough to use a relatively long FIR filter (e.g., 8 to 128 taps) for these frequencies.

K_p coefficient—the proportional coefficient (K_p) is dominant at medium frequencies (e.g., the frequency of the error signal is between about $f_s/1000$ and $f_s/10$, which is typically the frequency range where most of the transmission spectrum is located. Adaptation can much faster for these medium frequencies (e.g., 2 to 16 taps), in order to recover fast enough before a zero crossing of the comparator input difference with a high k_p setting leads to instability or even controlled oscillation with unnecessarily large amplitudes.

K_d coefficient—the differential coefficient (K_d) is dominant at high frequencies (e.g., $f_s/100$ up to $f_s/2$). Adaptation in this case can be very fast for this component and the length of the FIR filter can be significantly shorter (e.g., 2 to 4 taps).

FIG. **6** shows one embodiment of a more detailed estimator block **600** that makes use of these principles. In this embodiment, the estimator block **600** includes a shift register **602** coupled to the comparator (e.g., single bit comparator **402** in FIG. **5**) and configured to store successive single-bit values from the comparator in time. Additional gain scaling registers (e.g., a k_i register **604**, a k_p register **606**, and a k_d register **608**) can also be included and can store values derived from a combination of the single-bit comparator and the assist comparators (e.g., assist comparators **504** in FIG. **5**), if present. The estimator **600** also includes a look up table **610**, or some other block that executes a nonlinear mathematical function, to select a control coefficient based on values stored in the gain scaling registers.

As can be seen, the most recent samples of the coarse quantizer stored in the shift register are used to set the k_d coefficient. In contrast, additional older feedback samples out of the shift register are taken into account to set the k_i coefficient. Intermediate feedback samples out of the shift register are used to set the k_p coefficient.

A few non-limiting examples of how the coefficients can be calculated are set forth below:

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$$k_{i_rise} = \left| \sum_{v=0}^{n_i} S_{iv} \cdot s_{iv} \right| + \sum_{\mu=0}^{m_i} A_{i\mu} \cdot a_{i\mu}$$

with:

k_i gain rise factor for the integral path of the PID controller
 n_i number of shift registers taken into account
 m_i number of used assist comparators
 s_{iv} v clock periods delayed bit from the shift register [+1 or -1]
 S_{iv} weight factor for s_{iv}
 $a_{i\mu}$ output of the μ -th assist comparator [0 or 1]
 $A_{i\mu}$ weight favor for $a_{i\mu}$

$$k_{d_rise} = 1 + \left| \sum_{v=0}^{n_d} S_{dv} \cdot s_{dv} \right| + \sum_{\mu=0}^{m_d} A_{d\mu} \cdot a_{d\mu}$$

with:

k_{d_rise} gain rise factor for the proportional path of the PID controller
 n_d number of shift registers taken into account
 m_d number of used assist comparators
 s_{dv} v clock periods delayed bit from the shift register [+1 or -1]
 S_{dv} weight factor for s_{dv}
 $a_{d\mu}$ output of the μ -th assist comparator [0 or 1]
 $A_{d\mu}$ weight factor for $a_{d\mu}$

In some situations, the integral coefficient k_i can take the value 0 since it makes no sense to change the integral coefficient in cases where the error signal from the estimator indicates that the voltage output is extremely close to the target voltage. This setup is extremely stable and helps to ensure the output value quickly approaches the target value after slewing.

FIG. 7A-7C shows a series of simulation results as a series of waveforms. FIG. 7A shows circuit behavior of a sensor interface, which includes a single bit comparator without the use of an estimator to set PID coefficients. The upper plot in FIG. 7A shows two voltage curves as a sensor interface module attempts to transmit a PS15 sync pulse to one or more sensors. A single-bit comparator within the sensor interface module receives a target voltage 702 from a control unit, wherein the target voltage 702 represents the sync pulse to be transmitted. The single-bit comparator measures the output voltage 704, and regulates its internal currents (lower portion of FIG. 7A) in an attempt to have the output voltage 704 track the target voltage 702. In FIG. 7A's example, the single-bit controller does not have enough gain to track the target voltage 702, and hence the output voltage 704 provided by the sensor interface does not track properly.

FIG. 7B shows circuit behavior of another sensor interface, which includes a single bit comparator without the use of an estimator to set PID coefficients. In this example, the single-bit controller is fast enough that the output voltage 708 adequately tracks the target voltage 706 (as shown in the upper plot of FIG. 7B). However, the single bit comparator architecture creates high frequency transients on the output voltage line as well as in the delivered output current 710. Both will create electromagnetic emission and should be avoided.

FIG. 7C shows circuit behavior of another sensor interface, which includes a single-bit comparator and an estimator. FIG. 7C shows that the single-bit comparator with estimator is fast

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enough that the output voltage 712 adequately tracks the target voltage 714 (as shown in the upper plot of FIG. 7C). In addition, the inclusion of the estimator also reduces unwanted high frequency current transients (as shown in lower portion of FIG. 7C). In this way, the sensor interfaces disclosed herein provide good tracking ability for sensor interfaces, while simultaneously providing low power consumption and a reduction in electromagnetic emission.

Although the disclosure has been shown and described with respect to one or more implementations, equivalent alterations and modifications will occur to others skilled in the art based upon a reading and understanding of this specification and the annexed drawings

Further, it will be appreciated that identifiers such as "first" and "second" do not imply any type of ordering or placement with respect to other elements; but rather "first" and "second" and other similar identifiers are just generic identifiers. In addition, it will be appreciated that the term "coupled" includes direct and indirect coupling. The disclosure includes all such modifications and alterations and is limited only by the scope of the following claims. In particular regard to the various functions performed by the above described components (e.g., elements and/or resources), the terms used to describe such components are intended to correspond, unless otherwise indicated, to any component which performs the specified function of the described component (e.g., that is functionally equivalent), even though not structurally equivalent to the disclosed structure which performs the function in the herein illustrated exemplary implementations of the disclosure. In addition, while a particular feature of the disclosure may have been disclosed with respect to only one of several implementations, such feature may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular application. In addition, the articles "a" and "an" as used in this application and the appended claims are to be construed to mean "one or more".

Furthermore, to the extent that the terms "includes", "having", "has", "with", or variants thereof are used in either the detailed description or the claims, such terms are intended to be inclusive in a manner similar to the term "comprising."

What is claimed is:

1. A sensor interface module comprising;

a control unit interface configured to be coupled to a control unit;

a supply voltage module coupled to the control unit through the control unit interface and configured to output a target voltage signal;

a single-bit comparator or coarse analog to digital converter (ADC) having a first comparator input coupled to the supply voltage module and having a second comparator input coupled to an output node of the sensor interface module via a feedback path; wherein the single-bit comparator or coarse ADC is configured to provide a single-bit error signal which has a voltage level based on a comparison between the target voltage signal and an output voltage on the output node;

a sensor interface coupled to the output node of the sensor interface module and configured to be coupled to a pair of wires which are coupled to a plurality of sensors;

a proportional-integral-derivative (PID) controller having an input coupled to an output of the single-bit comparator or coarse ADC to receive the single-bit error signal; first and second controllable current sources having respective input terminals coupled to an output of the

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PID controller and configured to cooperatively establish the output voltage on the output node of the sensor interface;

an estimator coupled to the feedback path, wherein the estimator is configured to determine coefficients for the PID controller based on a history of bits on the feedback path;

a plurality of assist comparators having different respective trigger points and configured to help set the coefficients of the PID controller based on the history of bits on the feedback path.

2. The sensor interface module of claim 1, wherein the sensor interface is configured to provide a supply voltage to the sensors and to modulate the supply voltage based on the single-bit error signal output by the single-bit comparator or coarse ADC.

3. A sensor interface module comprising:

a control unit interface configured to receive a first control signal from a control unit,

wherein the first control signal corresponds to information to be transmitted to at least one of a plurality of sensors;

a supply voltage module coupled to the control unit interface and configured to output a target voltage signal based on the first control signal;

a single-bit comparator or a coarse analog to digital converter (ADC) having a first comparator input coupled to the supply voltage module and having a second comparator input coupled to an output node of the sensor interface module via a feedback path; wherein the single-bit comparator or coarse ADC is configured to provide a single-bit error signal which has a voltage level based on a comparison between the target voltage signal and an output voltage on the output node; and

a sensor interface coupled to a pair of wires which are coupled to both the plurality of sensors and the single-bit comparator or the coarse ADC, wherein the sensor interface is configured to provide a supply voltage to the sensors and to modulate the supply voltage based on the single-bit error signal;

a PID controller configured to output a second control signal based on the single-bit error signal;

first and second controllable current sources configured to receive the second control signal and cooperatively establish the output voltage on the output node based on the second control signal;

an estimator coupled to the feedback path, wherein the estimator is configured to determine coefficients for the PID controller based on a history of bits on the feedback path;

wherein the estimator comprises:

a shift register coupled to the single-bit comparator or coarse ADC and configured to store successive values of the single-bit error signal from the single-bit comparator or coarse ADC in time; and

a look up table configured to select a coefficient for the PID controller based on the successive values of the single-bit error signal stored in the shift register.

4. A sensor interface module comprising:

a control unit interface configured to receive a first control signal from a control unit, wherein the first control signal corresponds to information to be transmitted to at least one of a plurality of sensors;

a supply voltage module coupled to the control unit interface and configured to output a target voltage signal based on the first control signal;

a single-bit comparator or a coarse analog to digital converter (ADC) having a first comparator input coupled to

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the supply voltage module and having a second comparator input coupled to an output node of the sensor interface module via a feedback path; wherein the single-bit comparator or coarse ADC is configured to provide a single-bit error signal which has a voltage level based on a comparison between the target voltage signal and an output voltage on the output node; and

a sensor interface coupled to a pair of wires which are coupled to both the plurality of sensors and the single-bit comparator or the coarse ADC, wherein the sensor interface is configured to provide a supply voltage to the sensors and to modulate the supply voltage based on successive values of the single-bit error signal;

a PID controller configured to output a second control signal based on the single-bit error signal;

first and second controllable current sources configured to receive the second control signal and cooperatively establish the output voltage on the output node based on the second control signal;

an estimator coupled to the feedback path, wherein the estimator is configured to determine coefficients for the PID controller based on a history of bits on the feedback path; and

a plurality of assist comparators having different respective trigger points and configured to help set the coefficients of the PID controller based on the history of bits on the feedback path.

5. The sensor interface module of claim 3, wherein the estimator block comprises a logic unit configured to calculate a mathematical function to determine the PID coefficients.

6. A sensor interface module, comprising:

a control unit interface configured to receive a first control signal from a control unit, wherein the first control signal corresponds to information to be transmitted to at least one of a plurality of sensors;

a supply voltage module coupled to the control unit interface and configured to output a target voltage signal based on the first control signal;

a single-bit comparator or a coarse analog to digital converter (ADC) having a first comparator input coupled to the supply voltage module and having a second comparator input coupled to an output node of the sensor interface module via a feedback path; wherein the single-bit comparator or coarse ADC is configured to provide a single-bit error signal which varies in time and which has a voltage level based on a comparison between the target voltage signal and an output voltage on the output node;

a sensor interface coupled to a pair of wires which are coupled to both the plurality of sensors and the single-bit comparator or the coarse ADC, wherein the sensor interface is configured to provide a supply voltage to the sensors and to modulate the supply voltage based on successive values of the single-bit error signal;

a PID controller configured to output a second control signal based on the single-bit error signal;

first and second controllable current sources configured to receive the second control signal and cooperatively establish the output voltage on the output node based on the second control signal; and

an estimator coupled to the feedback path, wherein the estimator is configured to determine coefficients for the PID controller based on a history of bits on the feedback path;

wherein the single-bit error signal and feedback path are each a single bit variable, and wherein the estimator is configured to determine the coefficients for the PID con-

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troller based on a number of single bits provided on the feedback path at different times.

7. The sensor interface module of claim 3, further comprising:

a demodulation unit coupled to the pair of wires; wherein the demodulation unit is configured to receive a incoming signal from the at least one of the plurality of sensors by measuring current output onto the pair of wires by the at least one of the plurality of sensors.

8. A sensor interface module, comprising:

a control unit interface configured to be coupled to a control unit;

a supply voltage module coupled to the control unit through the control unit interface and configured to output a target voltage signal;

a single-bit comparator or coarse analog to digital converter (ADC) having a first comparator input coupled to the supply voltage module and having a second comparator input coupled to an output node of the sensor interface module via a feedback path; wherein the single-bit comparator or coarse ADC is configured to provide a single-bit error signal which has a voltage level based on a comparison between the target voltage signal and an output voltage on the output node;

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a sensor interface coupled to the output node of the sensor interface module and configured to be coupled to a pair of wires which are coupled to a plurality of sensors;

a proportional-integral-derivative (PID) controller having an input coupled to an output of the single-bit comparator or coarse ADC to receive the single-bit error signal; first and second controllable current sources having respective input terminals coupled to an output of the PID controller and configured to cooperatively establish the output voltage on the output node of the sensor interface;

an estimator coupled to the feedback path, wherein the estimator is configured to determine coefficients for the PID controller based on a history of bits on the feedback path;

a shift register coupled to the single-bit comparator or coarse ADC and configured to store successive single-bit values from the single-bit comparator or coarse ADC in time; and

a look up table configured to select a coefficient for the PID controller based on the successive single-bit values stored in the shift register.

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